

LUNAR SURFACE TRANSPORT VEHICLE

Abstract

A vehicle is needed to transport lunar soil from a mining site to a factory on the surface of the moon. The vehicle should be able to withstand the harsh lunar environment and need minimal maintenance and upkeep. It should also be easily modified to carry other loads if necessary.

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LUNAR SURFACE TRANSPORT VEHICLE

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1. PROBLEM STATEMENT

In order to support possible future mining operations on the moon, NASA is looking to design a vehicle to transport materials over the lunar surface. We have evaluated many different components taking into consideration the extremely harsh environment of the moon's surface. This report outlines our investigation and explains our design decisions.

2. OBJECTIVES

2.1 Purpose

The Lunar Surface Transport Vehicle (LSTV) will be capable of carrying 5 tons of moon soil. It should also be easily modified to carry other loads across the lunar surface.

2.2 Performance

The LSTV should be able to carry 5 earth tons of lunar soil from the mining site to the factory. The maximum incline will be 15 degrees and the cruising speed should be 15 mph (24 kph). The vehicle should only need to be refueled once in a 24 hour period and will be operated during the lunar day.

2.3 Manufacturing

The cost of manufacturing means little in comparison to reliability and weight considerations. The parts used on the LSTV should be of the highest quality to minimize down time or needed maintenance. The weight should be minimized due to the high cost of transport to the moon.

3. CONSTRAINTS

3.1 Size and Weight

The LSTV is large enough that it must be transported to the moon by space shuttle so it must be small enough to fit into the shuttle cargo bay (15 feet wide). Weight is also an important constraint, not so much from a payload aspect, but from a cost aspect: the cost of materials and fabrication is very small compared to the cost of transporting the vehicle to the moon's surface: about \$15,000 per pound. It should therefor be as light as possible.

3.2 Traction

The environment on the moon is very different than on the earth. For example, traction is greatly reduced by the decrease in gravity and the nature of the lunar soil. The gravity on the moon is one sixth of that on earth and the soil, on the average, is a very fine

sand-like substance. Also, when it comes to braking, it is important to note that although an object's weight is reduced to one sixth, its momentum is still the same. Driving a vehicle on the moon is fairly analogous to driving a car on ice. Because of the nature of the soil, steering can also prove to be difficult. Turning a tight radius at low speed can cause scrubbing and the vehicle could possibly dig itself into a 'hole'.

3.3 Temperature

The temperature extremes on the moon are also very important. The moon has no atmosphere to absorb any of the sun's radiation during the 'day' (which lasts about 14 'earth days'). Consequently, the surface of the moon reaches a maximum temperature of about 400 degrees Kelvin (127 degrees Celsius). And during the 'night', the surface temperature goes down to about 120 degrees Kelvin (-153 degrees Celsius).

3.4 Vision

The scattering effect that the moon's surface has on sun light as well as the absence of an atmosphere can greatly limit vision in some instances. For

example, with the sun low behind a vehicle, the landscape ahead of it would appear washed out and devoid of detail.

3.5 Vacuum

Again, because of the lack of an atmosphere on the moon, there is a very high vacuum. This lack of air brings up many interesting problems. The microscopic dust present on the moon cannot be blown away or vacuumed up when it gets on instruments and this is important because this dust is very abrasive. Fluids cannot be used because they would flash in a vacuum. The presence of a vacuum also dis-allows the use of rubber or plastic. These materials would outgas very quickly on the moon.

3.6 Abrasive Dust

As mentioned earlier, this dust on the surface of the moon is very abrasive and microscopic. Due to the vacuum and electrostatic forces it also tends to "stick" to surfaces and the low gravity allows it to travel very far when stirred up. The Apollo Astronauts discovered the importance of controlling this dust when a fender on the lunar rover would break. Because it is highly abrasive, all moving parts must be sealed from this dust.

4. FINAL DESIGN

4.1 Description

The Lunar Surface Transport Vehicle (LSTV) will be a rigid frame vehicle which will transport five earth tons of material from a mining site three miles miles to a factory site (see figure 4.1). The vehicle will have four wheels, all powered and steered. The electric motor will be centrally located and will run at a fixed rate. The motor will be connected to a Continuously Variable Transmission (CVT) with two output shafts, one to the front axle and one to the rear. Each axle will have a limited slip differential to give all wheels power even when one loses traction. The wheels will be solid with slats across three adjacent hoops to give traction. All control of the vehicle will take the place at the manned base either manually or automatically. The suspension system will use springs. A cooling system using a heat sink and a radiator will be used to dissipate heat. Hydrogen and oxygen fuel cells will be used to give power to the main motor and all the servomotors. A regenerative braking system using a hydraulic pump and compressional work, will stop the vehicle. Titanium and aluminum will be used as materials for most components. Because of its strength, titanium will be used for

significantly loaded components such as shafts, axles, and suspension parts. Aluminum will be used for the statically loaded components such as the hopper. All relatively moving parts will be protected from the dust by metal bellows. The vehicle's travel will be monitored by three on-board cameras which will transmit pictures back to the remote operation base.

4.2 Description of How the LSTV Will Be Used

Our vehicle will fit into the shuttle cargo shuttle bay lengthwise allowing for the transportation of 9 vehicles if the shuttle can carry the weight. There will be three transportation vehicles for each mining vehicle. The transportation vehicle will be loaded by the mining vehicle in a style much like a fork-lift. The vehicle will carry two hoppers and a total of 5 earth tons which is 1,666 pounds on the moon. The vehicle will move to the processing plant for unloading.

The vehicle is unmanned and is radio controlled by an operator at the processing plant. The controller will operate by visual means consisting of three video cameras. After a travel route has been established, some computer control of its guidance can be used with the operator taking over during loading and unloading. The average trip, assuming a six mile round trip, should last about 35 minutes. This allows

24 minutes travel time at 15 mph and 5 minutes each for loading and unloading.

At the processing plant, there will be an air lock big enough to fit the vehicle in. This will allow work to be done on the vehicle, like refueling and cleaning, without having to put on a spacesuit and spending hours adapting to it. When the vehicles are not being used, they will have to be heated so the coolant does not freeze. The coolant is water-based with anti-freeze for extra protection.

5. COMPONENTS

5.1 Introduction

In this section entitled Components we will discuss in detail our objectives, decisions, and designs of each component of this vehicle.

5.2 Motor (see appendix 1)

Introduction: The motor is a critical part of the LSTV. We would like a light weight efficient motor that will run on DC power. If the motor needs cooling, it needs to be designed so that it can be liquid cooled due to the absence of convection currents.

Alternates Considered: (1) Rocket thrusters

- (2) P.M. disc or drum
- (3) P.M. brushless
- (4) AC synchronous

Discussion: A permanent magnet brushless motor offered the lowest weight and highest efficiency. Given the weight of our vehicle, a maximum incline of 15 degrees and a 95% gear train efficiency, the motor power is 27 hp (20.25 kW). This size motor was difficult to find in P.M. brushless, also the weight would be high. The best alternative seemed to be to extrapolate a motor currently being used on the Space Shuttle. It is a 17hp AC synchronous motor weighing 17 pounds manufactured by Delco_Electronics. This motor uses samerium cobalt magnets to minimize size and weight. It also has a nonmetallic sleeve fitted into the stator bore for liquid cooling. Data for this motor is included and extrapolated to 27 hp for use in our design.

5.3 Fuel Cells

We investigated internal combustion engines, batteries, solar, and nuclear power as well, but decided on the hydrogen-oxygen fuel cell because:

- Its electrodes last longer than a conventional cell.

- It operates longer in between maintenance times.
- It has higher output per weight and volume.
- It uses conventional fuels, hydrogen and oxygen available right on the moon's surface.
- It is regenerative in the sense that its main by product, water, can be separated back into hydrogen and oxygen fuel.

We elected to use two 10kW fuel cells manufactured by Energy Research Corporation (a subsidiary of Fluor Corporation) to supply the 20kW needed by our vehicle. These cells are highly efficient (about 85%) and should be ideal for our purpose. They can operate for thousands of hours maintenance free and use a microprocessor for start up and to follow the load demands. This gives a startup time of under an hour and rectifies the power output automatically. We might also note that, although the technology is not yet available, the Triflourmethanesulphonic Acid Fuel Cell (TFMSA) could be ideal for our vehicle. It operates at higher power densities and lower temperatures.

5.4 Axle

The axles of this vehicle needs to be strong because of the loads they will be carrying. The design of the axle will also determine, to some degree, the

design of the steering, suspension, and frame and this must be thought about when choosing a design. We considered using solid axles like those used in the rear of rear-driven automobiles, half axles like those used on front wheel drive cars, and no axles. Our final design is based on the front axle of Ford Motor Company's four-wheel-drive large pickup trucks (see figure 5.4.a). This axle satisfies all of our objectives, however, it will be extensively modified from the ones used on the pickup trucks. First, we have to seal all of the exposed moving parts so that the lunar soil will not wear them down. There are three universal joints and the joints on the steering knuckles that will be sealed by using metal bellows. Another modification will be the use of a solid lubricant like graphite inside the differential instead of oil or grease because it is extremely difficult to seal a liquid lubricant from the vacuum present on the moon. The casing of the axle will be made of a different material, like titanium, to lower its weight; the dimensions of this axle will be changed to be six feet wide. Finally, the steering knuckles and the spindles will be changed to suit our steering system and wheels (see figure 5.4.b).

5.5 Steering

The choice of a steering system was an important

decision because it effected the overall configuration of our vehicle. For our purposes, we need a steering system that is highly maneuverable and can be operated remotely. We also tried to keep the wheels from scrubbing when turned. We considered three basic configurations. The first configuration called for 8 wheels divided onto two 4-wheel units which would be mounted on both ends of the vehicle and would rotate about their own axes (see figure 5.5.a). The second configuration we considered was an articulated design where we would connect two smaller vehicles together and have them move relative to each other to steer (see figure 5.5.b). Our final consideration, the one we eventually chose, is a four-wheel steering system using similar components to the front axle of a four-wheel drive vehicle here on earth (see figure 5.5.c). We chose this design because it is highly responsive and maneuverable and uses proven components. Another important factor is that it allows us to have a single solid frame structure and a single motor and transmission to save weight and complexity.

The two axles on our transporter similar to those used on Ford's large four-wheel-drive pickup trucks but are highly modified. The steering knuckles and linkages will remain very much the same; the linkage we will use is the Halten Berger Steering Linkage. This will be connected to a recirculating ball-type steering

gear. Torque to the steering gear will be supplied by remote-controlled servo motors, one on each axle. This configuration will satisfy all of our steering objectives (see figure 5.5.d).

5.6 Suspension

The suspension on this vehicle needs to be rugged and adaptable to our axle choice. One of our major constraints is that it needs to have as little moving parts or joints as possible to combat the abrasion problem brought about by the lunar dust. We considered three types of suspension designs: coil springs, leaf springs, and torsion bars. We chose coil springs because they have practically no parts that move relative to each other (leaf springs do). Coil springs also seemed to be more adaptable to our axle and frame designs (the torsion bars were not). The springs will be made out of spring steel because it is the most reliable material; we may coat the springs with a substance like graphite so that they will not wear down on the ends.

5.7 Wheels

Our objectives when choosing a wheel design are as follows: they must be able to support about 583 lbs each, they must have excellent traction, and they must be sturdy. On the moon we cannot use rubber or

plastics because they would disintegrate in the vacuum. We chose to use wheels instead of tracks because tracks would have too many joints which would have to be sealed from the abrasive dust. There were two types of wheel designs we considered, mesh wheels like those used on the lunar rover in the Apollo Program, and metal hoop wheels similar to those used on the Soviet Lunokhod 1 lunar probe. We chose the metal hoop design because we felt that it would give us a stronger wheel. It would also give us the good traction and high strength that we are looking for.

There will be four wheels each will have three adjacent hoops. Each of these hoops will be mounted on a high strength/low weight alloy wheel made out of aluminum or magnesium (see figure 5.7). All three of these wheels will be mounted to a common hub thus forming one of our "wheel units". The outer edges of these hoops will be connected to each other by a series of crossmembers or "traction slats" to give these units the strength and traction they need.

5.8 Brakes

Introduction: The moon and its $1/6$ gravity presents problems for braking. A moving vehicle has the same inertia as a vehicle on earth but has much less traction. The coefficient of friction on the moon's surface is also very low. We want to brake as quickly

as possible without losing traction and control.

A regenerative braking system became a desirable option because of the need to have as large a range as possible for our vehicle. The other advantage is that all of your braking energy isn't turned into heat which you would then have to conduct away.

Alternate Considerations:

- (1) Hydraulically lowered skid below the vehicle
- (2) Weights dragging behind the vehicle
- (3) Trip wires
- (4) Compressed gas thrusters
- (5) "Pogo stick" to absorb braking energy
- (6) Disc brakes
- (7) Regenerative braking
 - (i) Mechanical
 - (ii) Pneumatic
 - (iii) Momentum
 - (iv) Hydropneumatic

Because of dust problems, cooling problems, weight considerations, and the desire to regain as much energy as possible, a hydropneumatic design regenerative braking system was chosen

Discussion: A hydropneumatic regenerative braking system offered the best increase in range. The vehicle starts at rest with the accumulator at maximum

pressure. During acceleration the DC Motor is on and the accumulator is discharging and adding power through the power dividing gear. While cruising, the hydraulic motor/pump is in neutral so there is little drag on the drivetrain. To brake, the DC motor is taken off and all the braking energy is put into compressing the Nitrogen. There will be a relief line back to the LP fluid bellows to prevent overpressure in the accumulator. You can also charge the accumulator while cruising by switching the hydraulic motor from neutral to pump. This is not desirable to do all the time but the option is available if needed.

The weight of our vehicle was estimated at 14,000 earth pounds (6356 earth kg). The maximum speed of our vehicle is 20 mph (29.33 ft/sec or 8.95 m/sec). To decelerate to zero we must absorb 254 kJ of energy. The Nitrogen will absorb 97.84 kJ/kg so we will use 3 kg. The maximum accumulator pressure was set at 3000 psi (20.7 MPa) and the maximum pressure at 2000 psi (13.8 MPa). With these pressure valves, the volume of Nitrogen should fluctuate between 2.27 and 4.31 gal (.0086 and .0163 cubic meters) at 200 degrees Kelvin or between 5.12 and 7.66 gal (.0184 and .029 cubic meters) at 450 degrees Kelvin.

We can also calculate the maximum deceleration rate using a coefficient on friction of .05. To brake from 20 mph to zero would take 18.22 seconds. At 450

degrees Kelvin, the hydraulic motor would need to pump 2.54 gallons in this time, using a base 1200 rpm, the displacement of the pump needs to be 1.61 ci/rev (26.30 cc/rev).

We have now set all the critical values for our braking system. They are listed below:

Accumulator:

total volume : 15 gal. (.056 cub. m)
maximum pressure : 3000 psi (20.7 MPa)
gas : Nitrogen

Motor/Pump :

Displacement : 1.61 ci/rev (26.38 cc/rev)
Speed : 1,200 rpm

The low pressure fluid should be in a 15 gallon bellows that will keep the pressure at 50 psi (.345 MPa).

All of these components are readily available, even for space applications (see figure 5.8).

5.9 Cooling

Because there is no atmosphere on the moon, the only means of cooling is by conduction and radiation. The common method of cooling on earth, convection, is not possible in the lunar environment. To cool by

radiation, large panels, or radiators, are required. These radiators are usually covered by a metallic coating with a high emissivity.

The rate of cooling can be estimated by the basic equations of conduction and radiation namely:

$$q_c = -kA \left(\frac{\Delta t}{\Delta x} \right)$$

and

$$q_r = \epsilon \sigma A T^4$$

In these equations k is the thermal conductivity of a material, ϵ is the emissivity, and σ is Boltzman's constant.

In this design we considered two main areas of cooling: cooling of the motor and fuel cells and the cooling of the brakes.

Cooling of the motor and the fuel cells: We had to decide between two main methods of cooling for the motor and fuel cells. These two methods were heating a heat sink and dissipating heat into space. Since the motor and the fuel cells produce a large amount of heat, the motor 3000 watts and the fuel cells 3000 watts each at 85% efficiency, an extremely large radiator would be required to expel the heat. In this

light, we decided to use a combination of the heat sink concept and a radiator (see figure 5.9).

The cooling system will be separate so that there is easy access to the fuel cells and the main coolant tank. The motor will have coolant flowing through it to dissipate all of its heat. The coolant will then go through a heat exchanger where the heat will be transmitted to the heat sink. In this case the heat sink will be a large tank of coolant. The coolant heat sink will heat up while the vehicle operates and when the fuel cells are removed for recharging, the coolant tank will also be removed and cooled back down.

Since the fuel cells will have to be removed for recharging, they will be placed in the same removable compartment as the coolant tank. Since the fuel cells and coolant tank will not be separated, the coolant running through the fuel cells can run directly into the coolant tank, without the need of a heat exchanger. While the fuel cells are being recharged at the factory site, the coolant in the coolant tank will be cooled, thus the whole unit of fuel cells and coolant tank will be ready for another series of transports between the mining facility and the factory.

The radiator must perform most of the heat dissipation, because of the weight factor involved in carrying coolant on the vehicle. The more coolant carried the more the vehicle will weigh causing a need

for a larger motor and thus more heat production. The radiator will have small capillaries carrying the coolant. Therefore, heat will transfer from the coolant to the radiator and then to space. The radiator will be a square panel connected to a telescoping cylindrical support. When operation of the radiator is required the panel will point away from the sun. When entering the airlock for maintenance, the panel will be positioned horizontal and lowered as much as possible.

The coolant on the vehicle will have a specific heat of 1 BTU/lb F (4.186 J/gC). 50 gallons will be carried on the vehicle. The radiator will have a side length of 7.6 feet (2.33 meters) and will dissipate approximately 46% of the heat produced. The stored coolant will take on the remaining 54% of the heat.

In the case of heat being needed, the radiator can be pointed towards the sun as opposed to away from it to act as a heat collector.

Cooling of the brakes: Originally we designed the braking system as a frictional braking system. This would have required a large amount of cooling. However, a regenerative braking system has been decided on, meaning much less cooling is required. Consequently, the brakes along with the other parts of the vehicle, excluding the motor and fuel cells, can be cooled by conducting heat to the coolant tank.

5.10 Navigation and Control

We had two choices of control of our vehicle. We could either have our vehicle operate by a rider or operate remotely. One advantage of a rider operating the vehicle is that servomotors, radio transmission, and remote systems won't be needed. The advantages of using a remote system are that a rider won't be exposed to the harsh environment of the moon. Also, long hours of preparation are involved in preparing a person for a space suit. Furthermore, limitations exist on the time a person can be in a space suit. Because of these reasons, we chose a remotely controlled vehicle.

The vehicle will have several monitors of different types. It will have temperature monitors for the motors, fuel cells, coolant (inlet and outlet temperatures), and the radiator.

A pressure monitor will exist in each of the cooling subsystems. This will give information about pressure in case there is a leak.

Accelerometers will be mounted on various components to measure vibration. If an unusually large amount of vibration occurs, a warning light will alert the remote operator.

Three screens will be viewed by the remote operator. These three screens will correspond to the three cameras on the transport vehicle. One camera

will be mounted in the front fender and another will be mounted in the rear fender. These two cameras will have no motion. A third camera will be mounted on top of the vehicle and will be able to rotate 360 degrees. This camera and its mechanism will be encompassed by a clear encasing to keep dust away from it. The encasing will be within the focal length of the camera, thus any scratches or dirt on it will have little or no effect on sight.

To give better viewing quality, the screens at the operation base will each have a non-linear lens. This configuration was used for a remotely flown airplane and worked well. The system to be used on the vehicle will be similar using a broadcast quality television having a 525 line raster scan. Conventional transmission equipment will send the image information to the remote location. When received, the image will be projected by a light valve projector onto a hemispherical screen by another non-linear lens.

Sensors will give the speed of the vehicle, the motor rpm, fuel used, and transmission ratio.

Servomotors will be used in the pumps in the cooling system. They will be turned on and off when necessary. Also, a servomotor will control the opening and closing of the radiator umbrella and will control its motion. Furthermore, servomotors will control the braking, the motor, the locking and unlocking of the

hoppers, the steering, the transmission ratio control valve, and the top camera rotation.

A radio frequency antenna will be mounted on the vehicle to receive and send the controlling radio signals. This antenna will be shaped like a satellite dish. Back at the remote operation sight another antenna will be placed on the top of the building to receive and send signals.

At the remote operation a control panel will have the three camera views, the temperature readouts with warning lights, the coolant pressure with warning lights, warning lights for the vibration monitors, fuel consumption gauge, motor speed, transmission ratio, and degree of slope (see figure 5.10). Furthermore, a joystick will be on the panel so the operator can control the steering of the vehicle. Markings will be placed on the trail for the operator to follow. Two levers will be placed on each side of the steering joystick. The operator will use these to control the vehicle speed and braking. These levers will both be on the left so that the drive can switch from power to brakes without switching hands or taking his hand off the steering stick.

In addition, the vehicle will be able to be automatically controlled by a computer. The operator can put a run in computer memory and all he will have to do is to monitor the vehicle. The computer will

control all the servos on the vehicles. Unfortunately, the loading and the unloading of the vehicles will require manual operation.

The vehicle will not be run in the dark, but, it will still possess powerful headlights in the front fender. These lights will help with any shadowing problems from the vehicle.

If the vehicle is out of sight of the sending antenna, then a repeater station will be needed to transmit the signal from the vehicle to the remote operator.

5.11 Transmission

Some type of power transmission was needed to transmit power to the vehicle. The rover uses an electric motor which runs at 3500 rpm and develops 25 hp. The vehicle was designed with a 15 mph cruising speed the wheels turn at 140 rpm. The transmission and drivetrain had to have a reduction of 25:1 in order to match the constraining speed limits. Other constraints include weight, reliability, size efficiency, ease of control, and power transmission levels.

A continuously variable transmission was chosen because it suited the constraints better than a conventional automatic or manual transmission. A conventional automatic, like the kind used in

automobiles, has about 1000 parts, while the CVT has fewer than 400. This should mean a better reliability because there are less parts for something to go wrong with. The CVT also weighs less and is more efficient than a conventional automatic.

The problem with a manual transmission is that there is no driver on the rover to change the gears. Building a servo controlled shifter would prove to be very difficult because of the complexity. A manual transmission is more efficient than a CVT or an automatic, but the CVT is only a few percentages less efficient; 86-95% vs 95-98%. At low speed, the CVT seems to do better than the manual transmission and the rover will be traveling at low speed.

There are many CVT designs available today, but very few of them can handle the horsepower the rover motor possesses. A belt-driven design was chosen because of its power handling abilities, its simplicity, and its reliability. A modified version of the van Doorne transmission is used (see figure 5.11.a). It will have to be made to fit the motor housing. The transmission uses one steel belt between two pulleys to transmit power. The pulleys move to change the transmissions ratio.

The belt is made of an endless string of thin wedge blocks that run loosely over two thin laminated steel loops. The power is transmitted through the

blocks instead of the loops. The blocks are only held in place by the loop. The blocks push against each other to transmit power.

The loop is made of ten concentric bands of steel, each .2 mm thick so they possess strength and flexibility. The steel belt can turn around radiuses as small as 30.5 mm (see figure 5.11.b).

The ratio is changed when one pulley is hydraulically widened, while the other belt is simultaneously narrowed to match the fixed belt length. Ratios of up to 6:1 are possible by using larger pulleys. The ratio will be controlled by microprocessors. The speed of the vehicle will be controlled by the transmission instead of the motor. Electric motors run better at high speeds so the motor will stay at a constant high speed of 3500 rpm and the transmission will shift, thereby changing the speed.

The van Doorne transmission has been tested and proven to be reliable. The project chief was quoted as saying "Many of the 100 test cars with the prototype engine have covered 100,000 miles with no failures." The unique feature of this CVT is that the belt does not run in tension, but in compression. A belt run in tension would tend to separate the pulleys because of the driven torque. A compression run belt gives greater no-slip torque capacity than a tension belt. The entire belt assembly is immersed in traction

fluids, preventing wear between the belt and pulley.

When two objects are pushed against each other at a high pressure, like between the belt and the pulley, the fluid separates the two objects and it transmits the power between them. This separation prevents the belts and pulley from wearing out quickly.

The drivetrain has gearing at the center of the vehicle with two shafts running to the limited-slip differentials on each axle. A limited-slip differential was chosen so that if one wheel lost traction, the other wheel would still have power, giving the vehicle better traction. The gearing just after the transmission consists of two helical gear with ratios of 5:1. Power is outputted on both sides of the larger gear to universal joints. The shafts run to universal joints just before the differentials. The differential also has a reduction ratio of 5:1, giving the drivetrain a total reduction of 25:1.

To prevent dust from getting into the drive system, metal bellows surround everything that moves or needs to be sealed from dust.

5.12 Loading and Unloading.

The hoppers will be unloaded and loaded by the mining vehicle. The process is much like that of a trash truck loading a hopper. The hopper will be

loaded with materials and then placed on the transportation vehicle. Two arms will grasp the hopper and move it into position. The operator of the transportation vehicle will have to move it into position for loading and unloading because the mining vehicle will not be as maneuverable because of its size.

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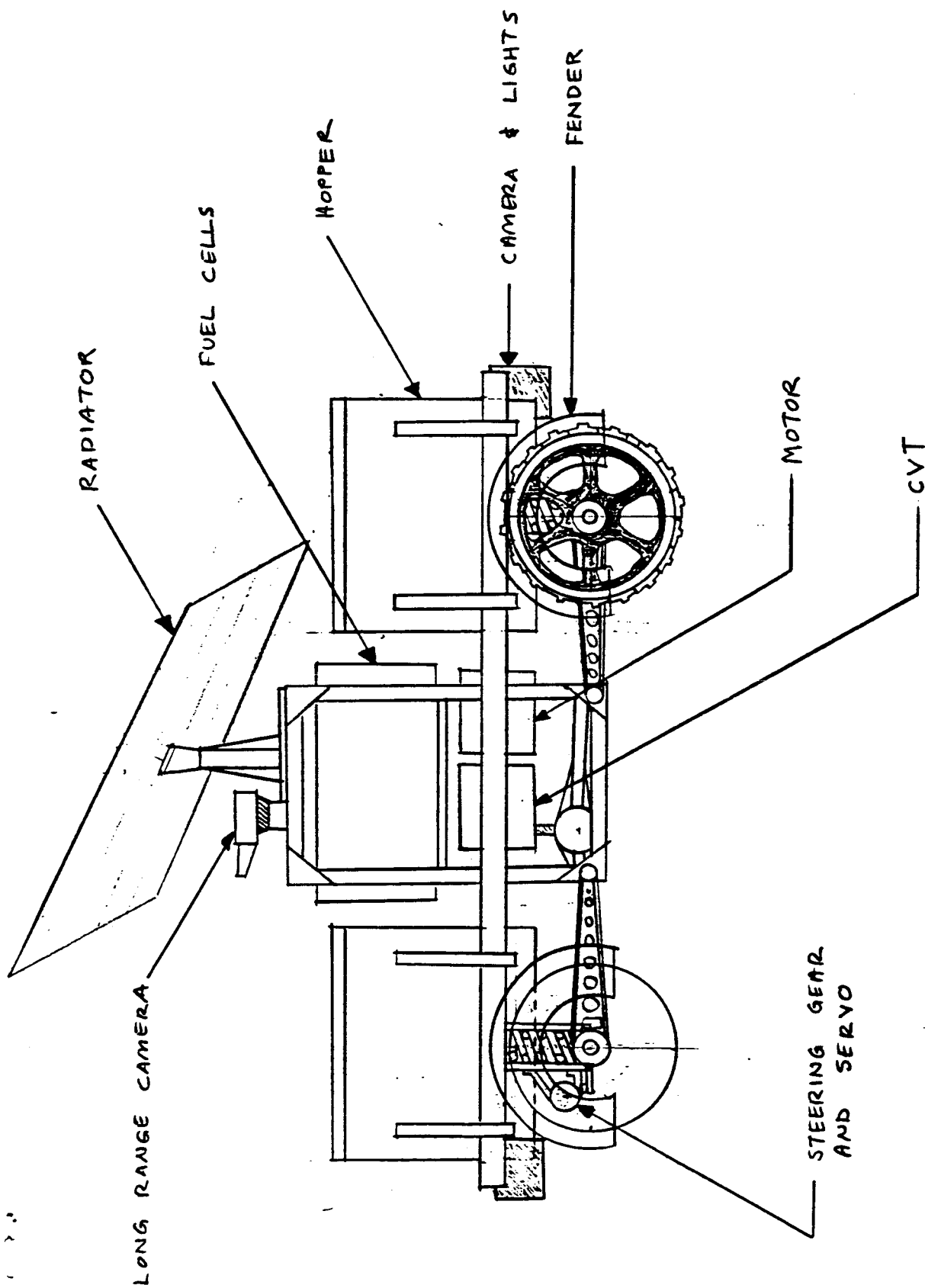


Figure 4.1
(L.S.T.V.)

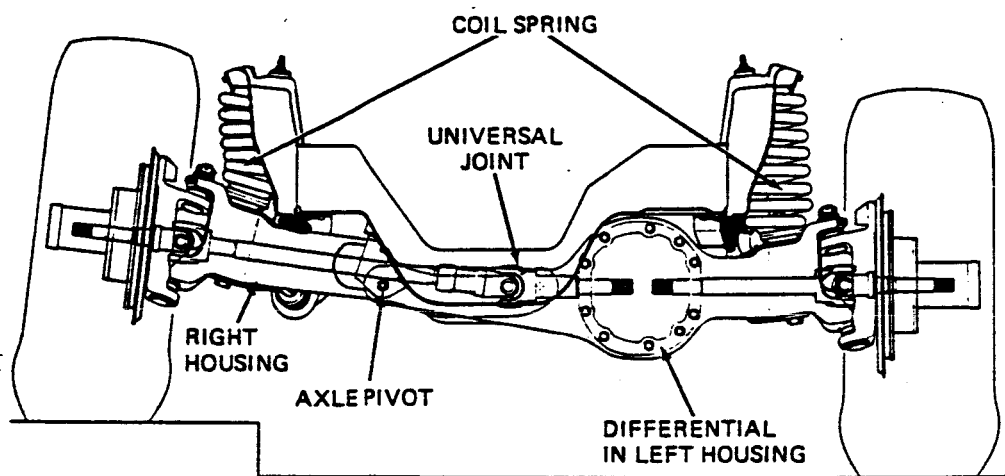


Figure 5.4.a
(Lunar transporter axle design)

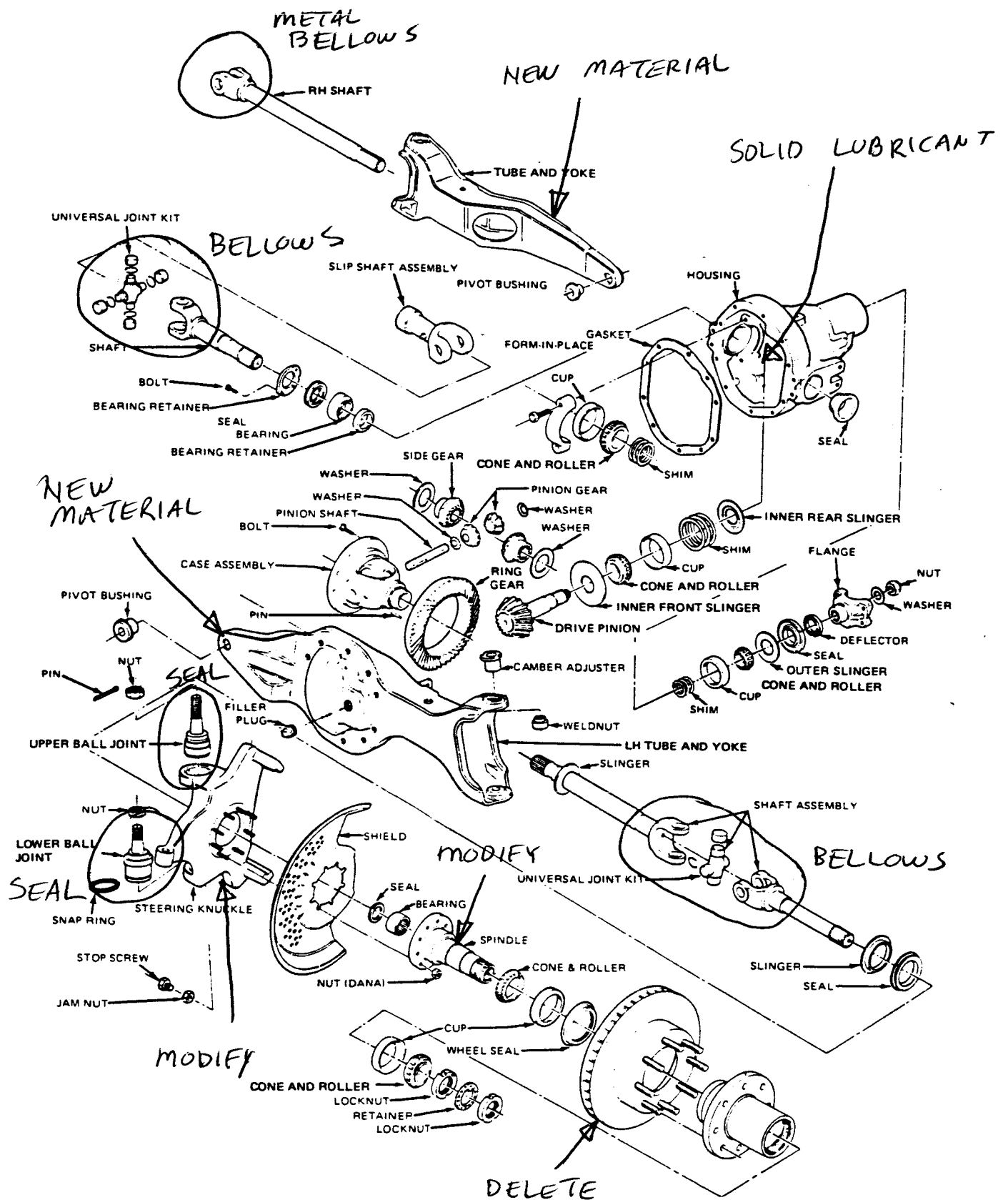


Figure 5.4.b
(Exploded View of Axle with Modifications Indicated)

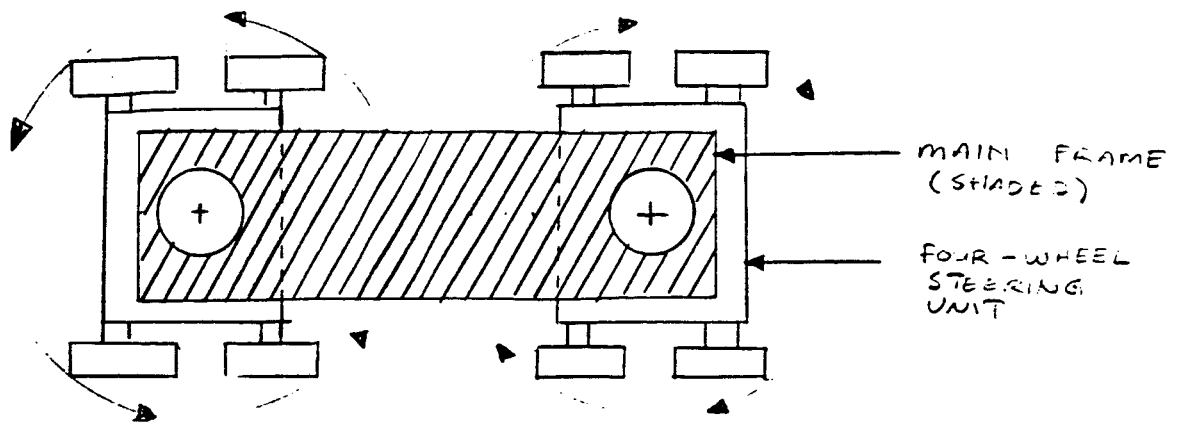


Figure 5.5.a
(Steering configuration)

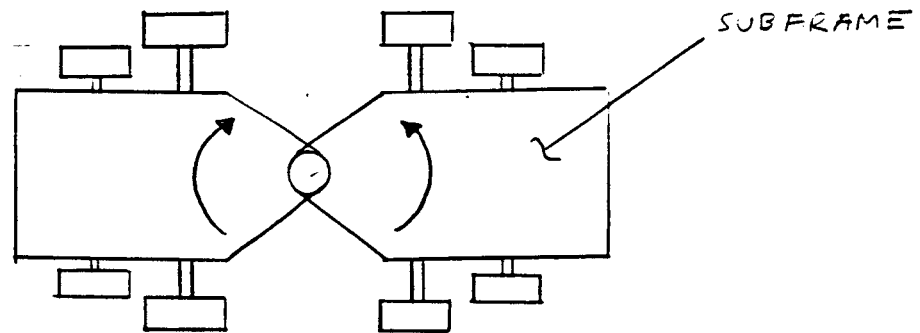


Figure 5.5.b
(Another possible steering configuration)

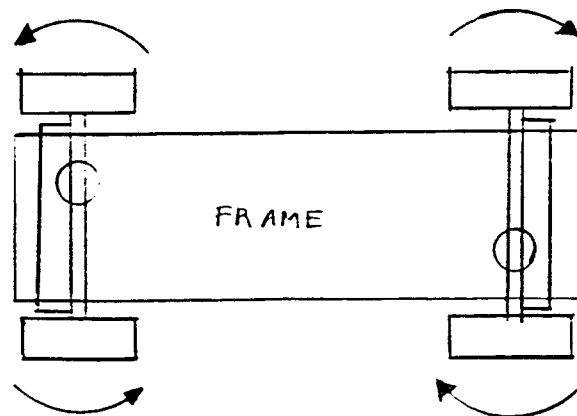


Figure 5.5.c
(Our final steering configuration)

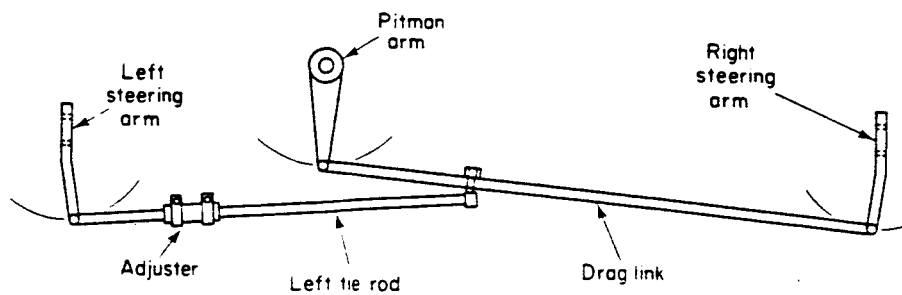
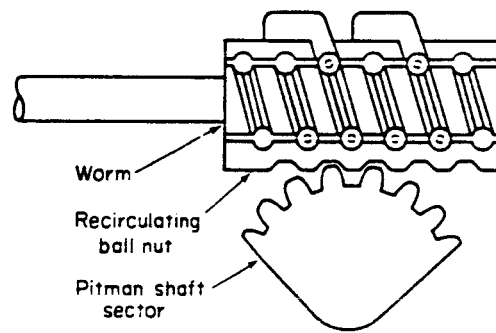
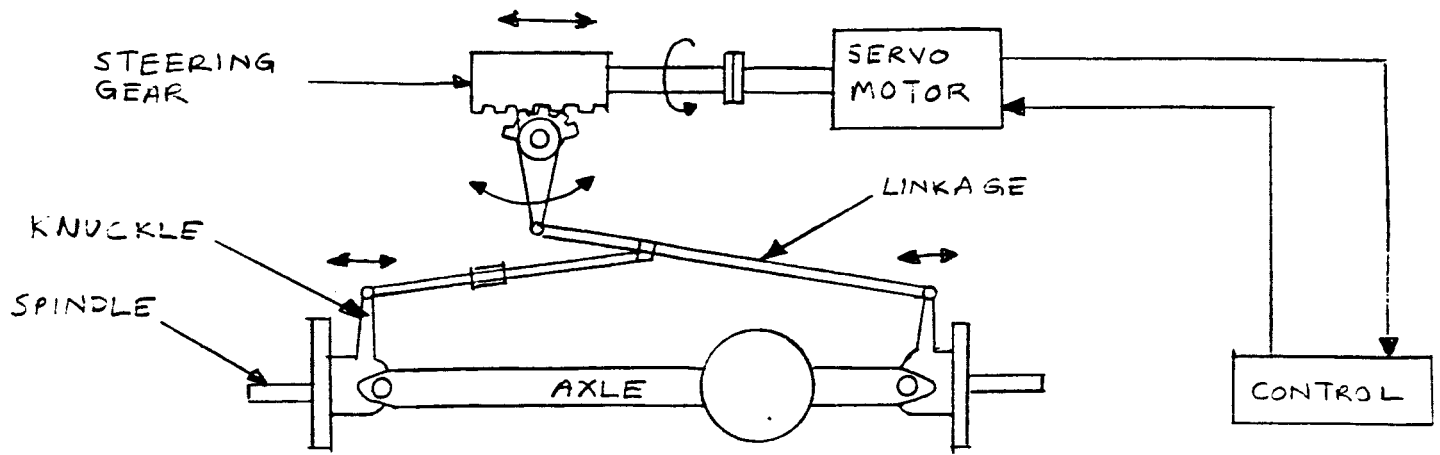


Figure 5.5.d
Steering Gear and Linkages

WHEEL DESIGN:

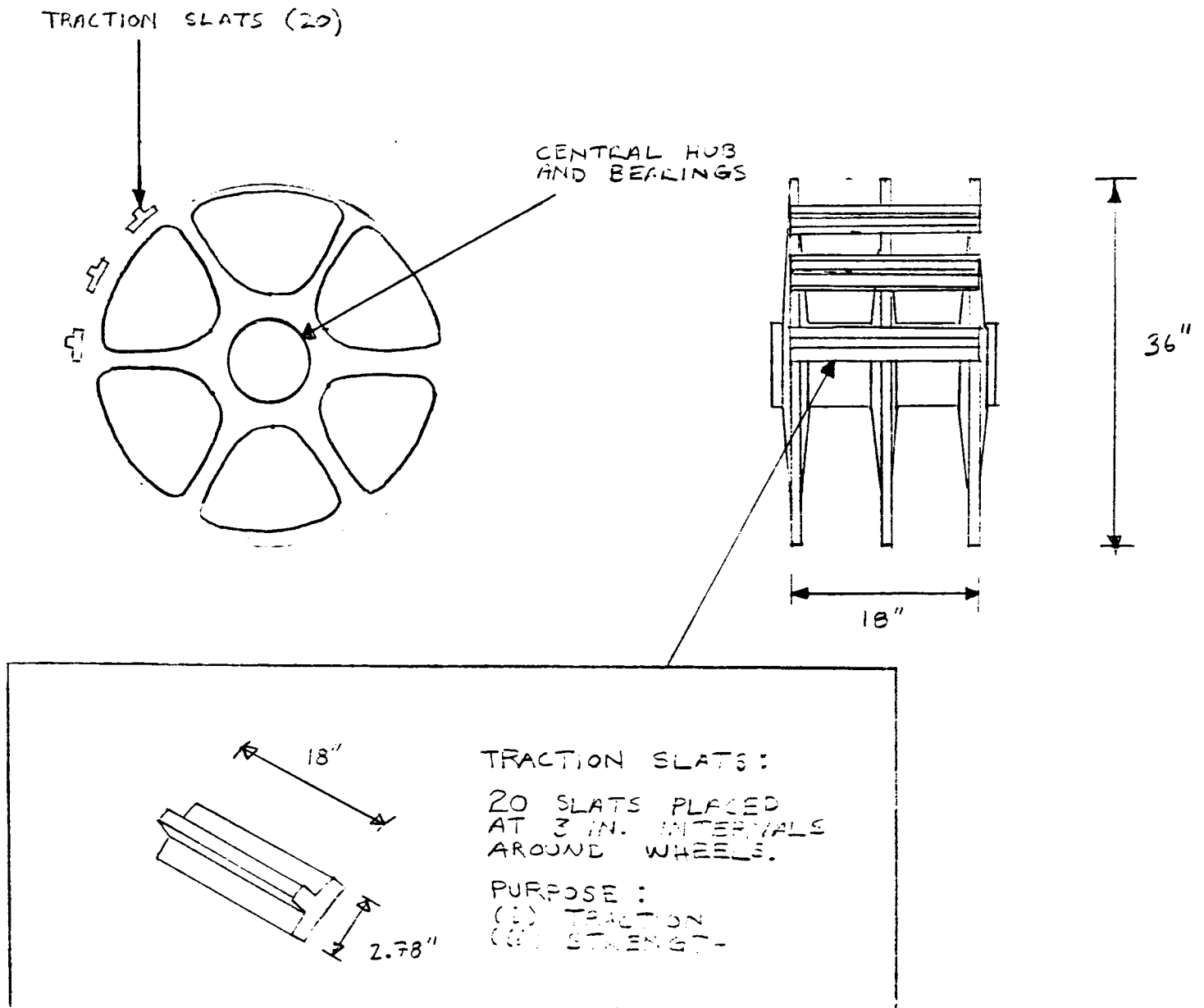


Figure 5.7
(Wheel Design)

DRIVE - BRAKE SYSTEM LAYOUT

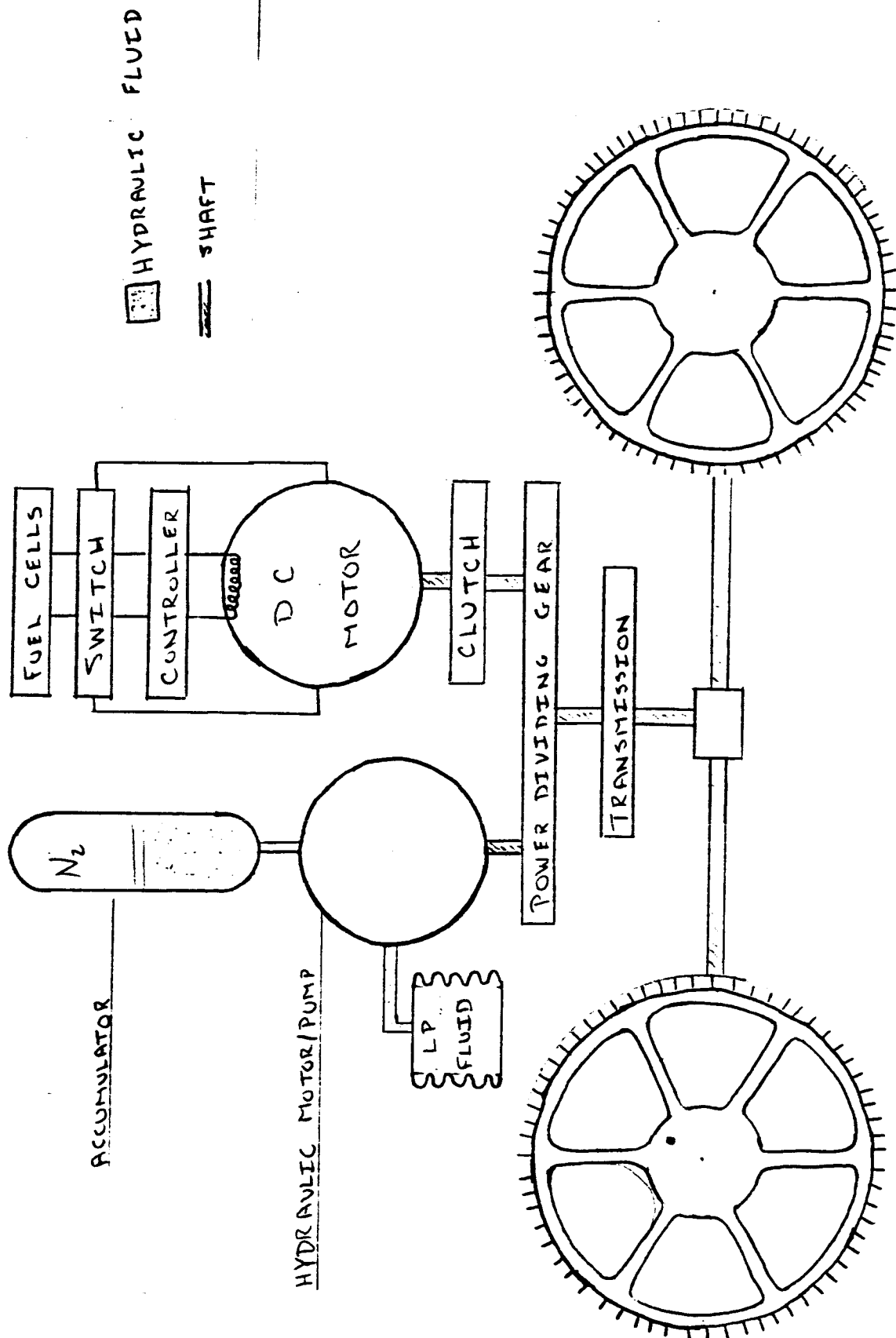


Figure 5.8
(Regenerative Braking)

Cooling System

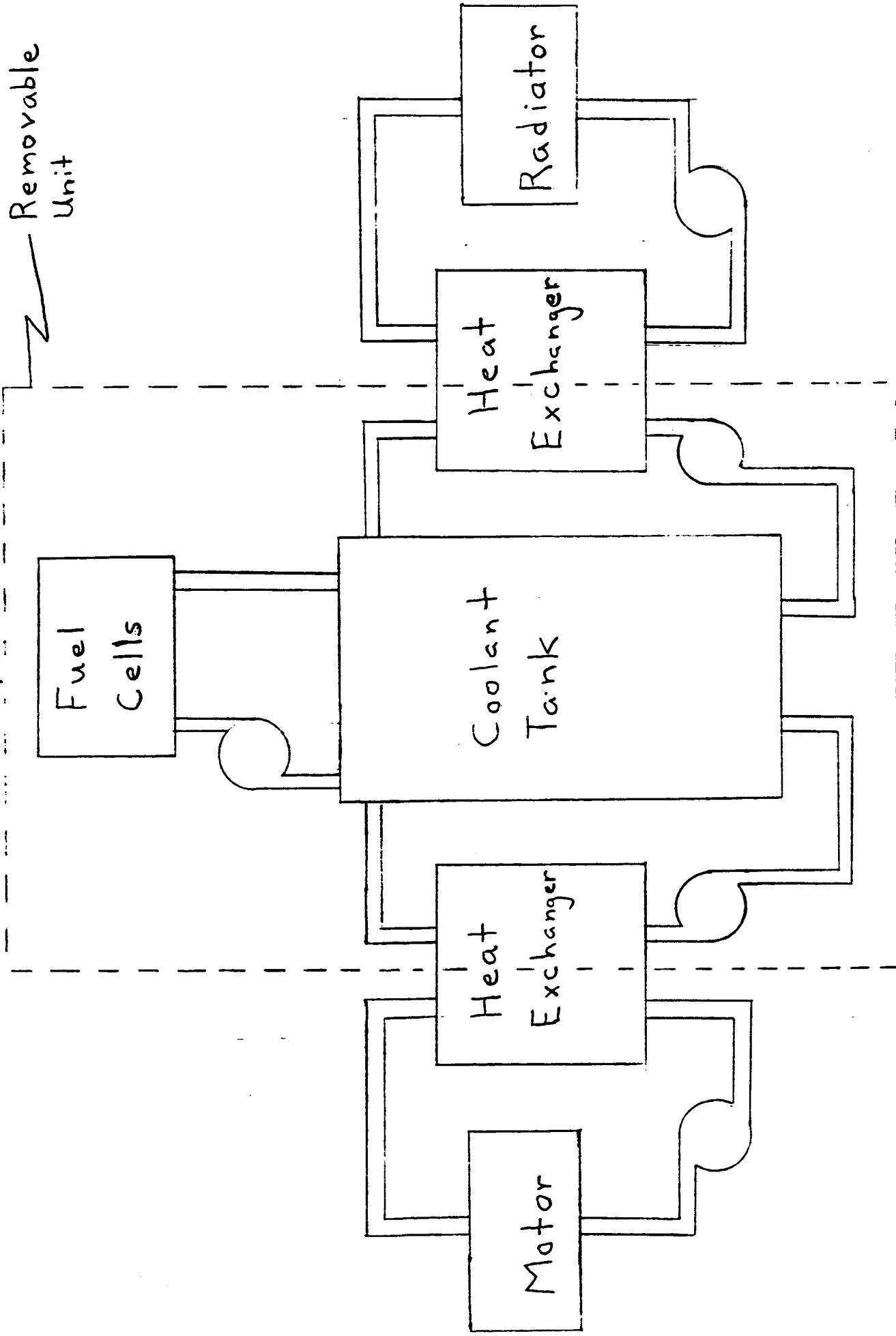


Figure 5.9
(Heat Sink and Radiator)

Navigation Control Panel

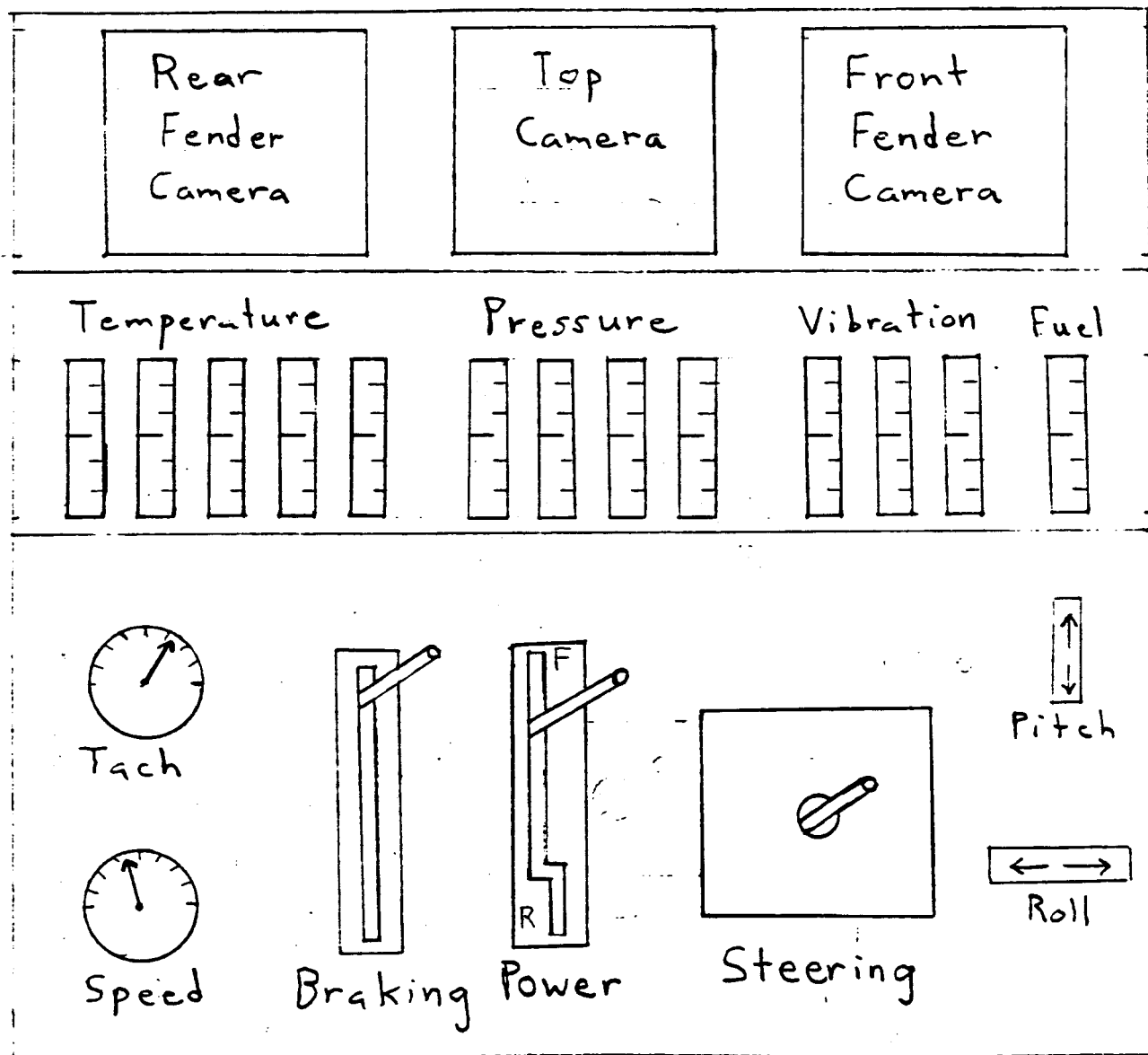


Figure 5.10
(Remote Control Panel)

Transmission

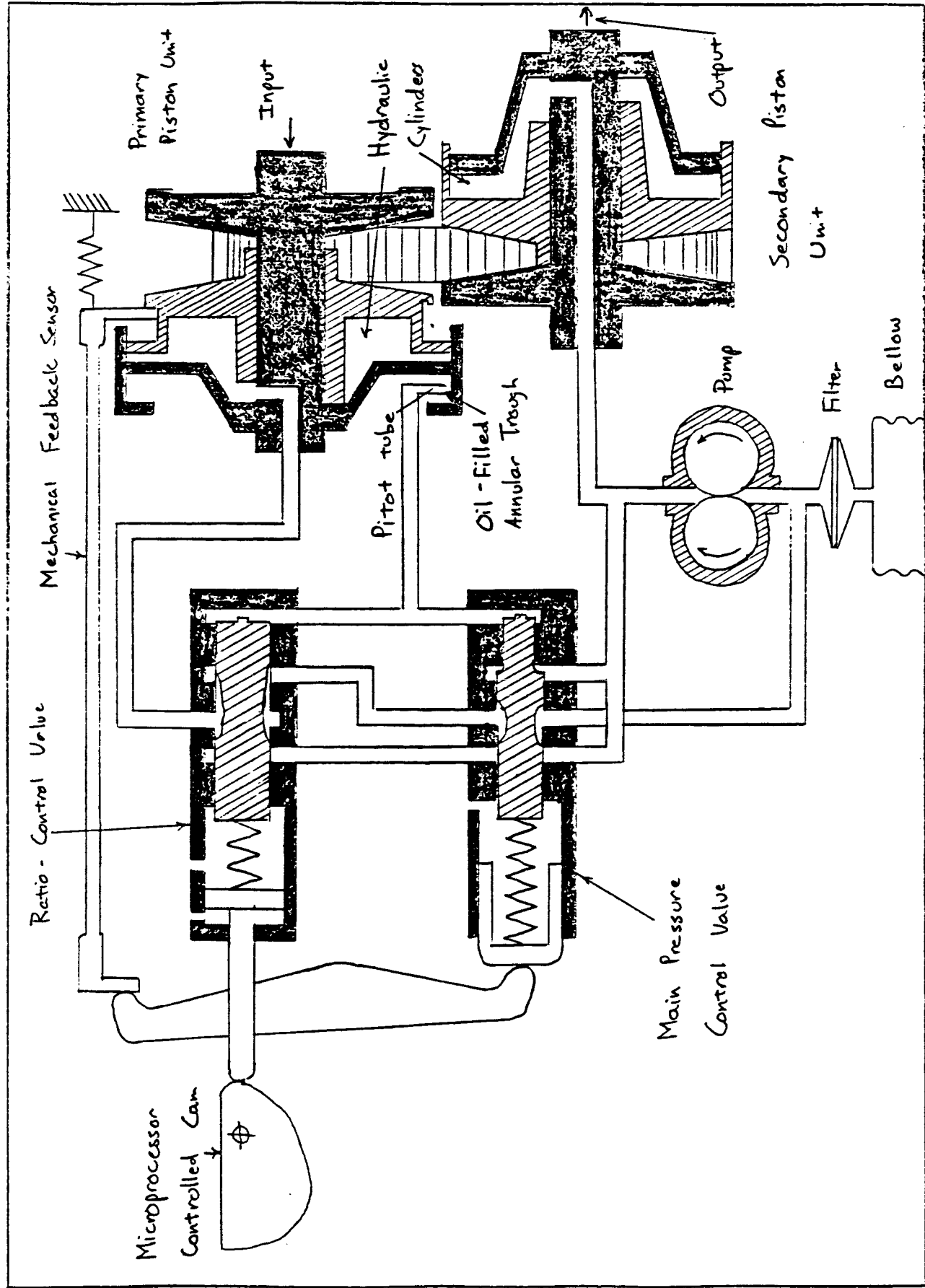


Figure 5.11.a
(Transmission Design)

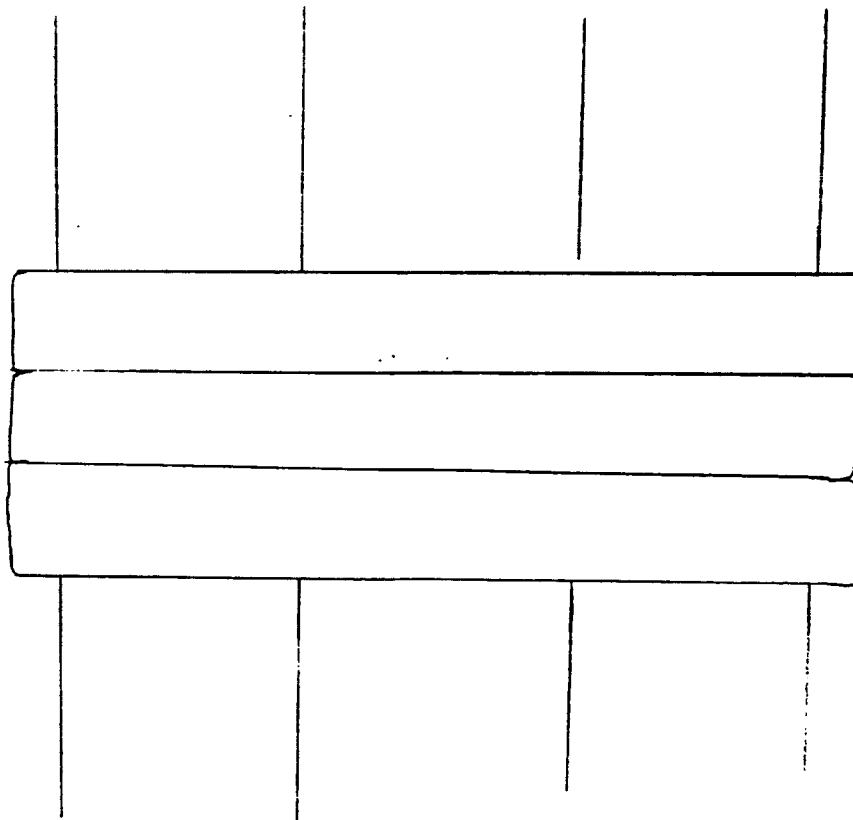
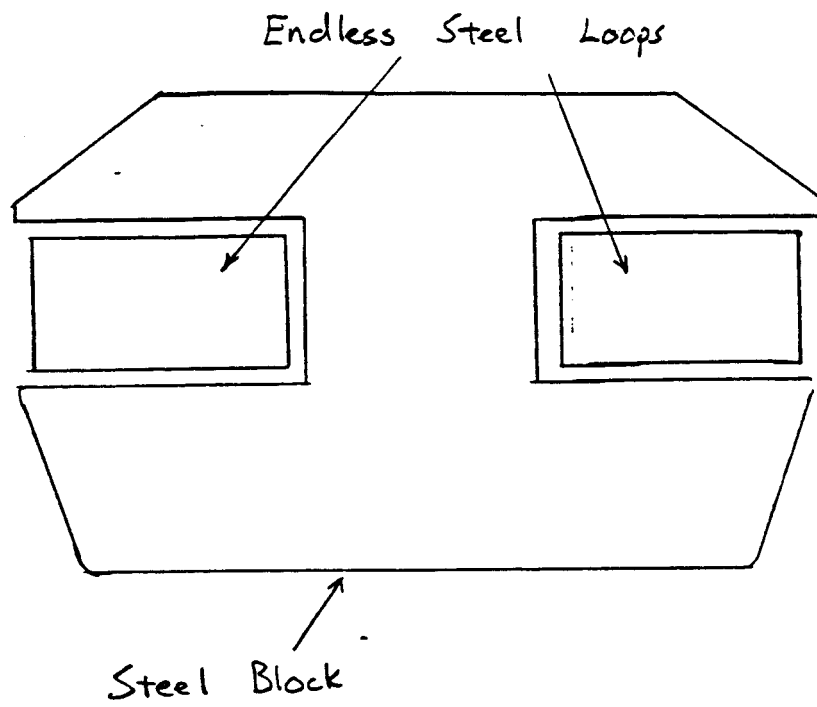


Figure 5.11.b
(Transmission Belt Design)

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ESA-BR-12: "Tribology"

JPRS-54525: "Lunokhod-1 Mobile Laboratory"
N70-18797: "Traction Drive"
N70-24259: "Ramjet Engines"
N70-29528: "Wire Mesh Wheels"
N70-32328: "Energy Conversion and Electric Propulsion"
N71-17507: "Electric Propulsion"
N71-21338: "Thermoelectrics and Lunar Explorations"
N71-32279: "Performance of Two Thermionics"
N72-12165: "Lunar Rover Vehicle"
N72-22885: "Rockets"
N72-25704: "Thermionics"
N74-15740: "Hopper Transporter"
N75-29141: "Jet Propulsion"
N77-26804: "Remote Manipulator System Steering
Capability for Space Vehicles"
N85-14512: "Visual Systems for Remotely Controlled
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UCRL-52306/1&2: "Regenerative Braking"

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Our Thanks To Gary Kelly for the Article on the Samarium-
Cobalt DC Brushless Motor

APPENDIX A

Team 7; Lunar Material Transport Vehicle Problem Statement
January 27, 1986

Problem: To design a surface vehicle to transport materials from a mining operation to a factory operation on the moon.

Constraints:

- Must be reusable
- Withstand lunar conditions
- Operable by one man
- Lightweight
- Must be able to fit in the cargo bay of the Space Shuttle

Performance Objectives:

- Ascend 15 degree slopes
- 200 mile range
- Payload of two earth tons
- Maximum speed of 15 mph

Lunar Surface Transport Vehicle Progress Report #2

February 3, 1986

Decisions Made to Date:

- 1) Load Capacity: 5 Earth Tons
- 2) Vehicle Weight: 2 Earth Tons
- 3) Wheel Configuration: 8 Wheels, All Drive
- 4) Two Motors, One Motor for Each Set of Four Wheels
- 5) Approximate Bed Dimensions: 8.5'x5'x2'
- 6) Friction Brakes with ABS
- 7) Compressed Gas for Emergency Brakes
- 8) Wheels in Groups of 4 Turn Together
- 9) Mechanical Linkage Steering
- 10) Open Cab
- 11) Motors Will be Electric
- 12) Hydraulic Lift for Bed

Ideas:

- 1) Cooling Brakes and Motors with Removable Heat Sink
- 2) Back of Bed Slanted for Easy Unloading or Tailgate
- 3) Landmark Navigation
- 4) Multitudes of Strategically Placed Temperature Sensors

Research Status:

We still have not received our search from the library.

Progress Report

2 BASIC CONFIGURATIONS

- 1) 2 MAIN STRUCTURES CONNECTED BY A PIVOTING JOINT.
PRO: EASIER TO TURN AT LOW SPEED AND AT REST.
- 2) 1 MAIN FRAME WITH TWO ROTATING SUBASSEMBLIES.
PRO: STABLER WHEN MOVING, MORE VERSITILE PAYLOAD
POSSIBILITIES.
CON: HIGH SCRUBBING WHEN STEERING.

THINGS DISCUSSED FEB 3 - FEB 10

- 1) INTERFACING WITH MINING AREA AND PROCESSING PLANT. WE SHOULD HAVE REMOVABLE HOPPERS TO HOLD THE PAYLOAD.
- 2) WE WILL BE USING 8 WHEELS. THERE WILL BE APPROX. 290 - 300 LBS. ON EACH WHEEL. THE SURFACE OF THE MOON CAN HOLD APPROX 1 - 5 PSI. OF SURFACE PRESSURE.
- 3) THE VEHICLE CROSS SECTION WILL BE APPROX. 9 FEET WIDE BY 6 FEET TALL BY 20 FEET.
- 4) FUEL CELLS WILL BE USED FOR THE POWER SOURCE.
- 5) REMOTE CONTROL WITH TV CAMERAS.
- 6) ROVER WILL BE USED TO CARRY FUEL TO THE MINING OPERATION.
- 7) REPEATER STATIONS WILL BE PLACED ALONG THE ROUTE TO TRANSMIT SIGNALS.

THINGS TO INVESTIGATE FURTHER.

- 1) COOLING SYSTEM.
- 2) REMOTE CONTROL.
- 3) SUSPENSION.

Team 7
2/17/86

Progress report

Finalized parameters.

- 1) Four wheels, all drive.
- 2) One motor to save on weight.
- 3) All wheel steering.
- 4) Fuel cells for power supply.
- 5) Remote control by cameras.
- 6) Continuously variable transmission.
- 7) Regenerative braking.
- 8) Cooling of motor by water heat sink.
- 9) Fuel cell and water heat sink will be removable for quick turn around times.
- 10) 40 horsepower closed electric motor.
- 11) Wheel size 3 ft high, 1.5 ft wide.

We split into five study areas consisting of:

- 1) Motors, regenerative braking.
- 2) Transmission.
- 3) Suspension and steering.
- 4) Cooling.
- 5) Fuel cells.

We will try to finalize details on these areas by next week and begin on five more areas at that time.

Team 7
2/24/86

Progress Report

New Developments

- 1) Have selected our choice of axle.
- 2) Have selected a steering system.
- 3) The suspension is coil spring design.
- 4) The motor will be a permanent magnet brushless motor.
- 5) We will use a Vadetec Nutating Cone and Ring CVT.

New Areas of Research

- 1) Servo control of steering.
- 2) Feedback control of motor by PWM.
- 3) Wheel structure and sealed bearings.
- 4) Cameras and remote control.
- 5) Regenerative braking.
- 6) Temperature monitoring.
- 7) Heat output of fuel cells and motors.

Progress Report

New Developments

- 1) Hydropneumatic regenerative braking system.
- 2) Recirculating ball type controlled by a servo motor.
- 3) Hopper will be loaded by the mining group and possibly unloaded by the factory group. If not, we will use the self dump design.
- 4) Transmission has been changed to a steel belt design. The new design has been tested more than the rotating transmission and was found to have a very high reliability.
- 5) Motor is 250-V, 80-A and a operating speed of 3500 rpm.

New Areas of Concern

- 1) How to keep dust off the camera lenses.
A wiper with protective glass over the lense.
Charge reversal to repel the dust.
- 2) Navigation and controls.
- 3) Metal Bellows to keep dust from moving parts.
- 4) Hopper will fit between the two main body rails.

We have divided up the report into sections, each being written by group members who studied the area. We are working on getting a CAD drawing done. We will have drawings of:

- 1) The transmission.
- 2) The suspension and steering.
- 3) The braking and motor system.
- 4) The completely assembled vehicle.
- 5) The support and frame for the hoppers.

Progress Report

- 1) We figured out the size of the radiator and the amount of coolant needed.
- 2) We need a total of 25:1 reduction in the drivetrain.
- 3) Calculated the kilograms of nitrogen needed, the total size of the accumulator, the capacity of the hydraulic motor/pump.
- 4) Decided that we need various sensors like thermocouples, accelerometers, pressure sensors, tachometer, speedometer, transmission ratio monitor, and fuel consumption meters.

We have done drawings of the following:

- 1) Overall vehicle view.
- 2) Cooling system schematic.
- 3) Transmission.
- 4) Regenerative braking system.
- 5) Wheels and suspension.
- 6) Steering linkages.
- 7) Previously rejected steering systems.

APPENDIX B

copy
D.2.

DESIGN OF A SAMARIUM COBALT BRUSHLESS DC MOTOR FOR ELECTROMECHANICAL ACTUATOR APPLICATIONS

Bert Sawver

Delco Electronics Division
General Motors Corporation

J. T. Edge

National Aeronautics and Space Administration
Johnson Space Center

ABSTRACT

This paper describes a samarium-cobalt, permanent-magnet, brushless dc motor which was designed, fabricated and tested as a prime mover for an electromechanical (EM) actuator. The parameters of the motor were tailored to meet the performance requirements of the Space Shuttle Orbiter elevon. The operational constraints of the elevon required a lightweight high-efficiency motor, with a permanent magnet rotor, and the capability of operating from a high voltage battery power source. Regenerative braking was specified to minimize total energy requirements. Rated at 17 HP, the resultant motor can accommodate high duty cycles in high power, high performance servo applications, while expending power only in proportion to its load conditions.

INTRODUCTION

The National Aeronautics and Space Administration is sponsoring a program to establish the feasibility of using electromechanical actuators to drive primary flight control surfaces. Conventional primary flight control actuation systems have typically been based upon electrohydraulic actuator technology. However, recent advances in high performance, rare earth, permanent magnet materials and in high power semiconductors have made the electromechanical actuator an attractive alternative.

In brushless dc motor designs, the use of rare earth, permanent magnet material can significantly reduce motor weight, and increase efficiency. Such motors output a high torque, have a low rotor inertia, and are highly responsive. Simple logic circuitry can be used to sequence power semiconductors to control both motor torque and velocity.

Using such material and technology, Delco Electronics designed, fabricated and tested a lightweight, high efficiency brushless dc motor which is rated at 17 hp, and capable of high duty cycles in high power, high performance servo applications. Because the motor expends power only in proportion to load conditions, its losses are minimized.

In this machine, the rotor consists of samarium-cobalt magnet segments attached to an eight sided shaft; banding and balancing complete the rotor assembly. Construction of the stator assembly is conventional. The power electronics consists of a series current regulator, preceding the commutation circuit, to provide control of motoring torque. A shunt current regulator provides regenerative braking.

Laboratory test data generally shows flux levels and motor efficiency higher while phase inductance, resistance, and cooling requirements were lower than predicted.

MOTOR CONCEPT

This motor concept—which represents a departure from conventional design—is a brushless, rare earth permanent magnet rotor, ac synchronous machine made self-synchronous by the addition of a rotor position sensor. In size, weight, reliability, and maintainability this type of machine offers significant advantages over dc motor. Compared to ac induction motor, it has higher efficiency (due to its near unity power factor and low harmonic distortion), permits a simple direct power inverter control, and requires no rotor cooling.

The motor utilizes a commercially available, rare earth permanent magnet material; this provides a high torque-inertia ratio for good frequency response. The rotor position sensor is used to sequence power semiconductors which commutate a three phase stator winding. Positive and negative torque (as required for servo applications) is provided by controlling the commutation sequence.

The stator windings are air-cooled, or liquid-cooled (if required) by directing coolant through the stator slots. In the latter case, a nonmetallic sleeve in the air gap seals the stator and prevents coolant from contacting the rotor. Important advantages of this machine are that:

- The main pole flux is always present. This is important in servo applications, which tolerate no delay in flux build-up (as in a wound rotor machine).
- No standby power is required to maintain the flux while awaiting application of stator power.
- The rotor has essentially no losses. There are no windings on the rotor poles, and the smooth rotor surface has negligible windage loss. Iron losses are low because of the resistivity and low permeability of the permanent magnet material and by proper design of the stator-slot air-gap-length ratio to minimize the amplitude of the ripple flux in the pole face.
- The air gap length is not critical to the design. Therefore, since a relatively long air gap may be used, a nonmetallic sleeve may be inserted in the air gap for cooling purposes.

*Campbell, et al. Vehicle Propulsion and Control System. Patent No. 3,297,926 (1967).

High performance permanent magnet motors are difficult to design using Alnico materials. Although such materials have adequate induction levels, their coercive forces are low (less than 1.0 kOe). Motors designed with Alnico magnets often fail when the machine encounters a higher-than-rated current pulse, such as with force-commutated SCR controls during the turn-off portion of the cycle.

Rare earth cobalt magnets are now available having residual induction levels above 8.0 kG and coercive force exceeding 8.0 kOe. Use of such material in a motor provides a maximum flux field from a minimum volume of magnetic material, thereby minimizing the size and weight of the magnetic circuit.

MOTOR DESIGN

Requirements

The EM Actuator requirements were based on those of the Space Shuttle Orbiter elevon (Table 1) whose operational constraints required a motor capable of operating from a high voltage, battery power source; regenerative braking was required to minimize total energy requirements.

CONDITION	DR (%)	RATE (Deg/Sec)	HM (In-Lb x 10 ³)
I. Steady State Limit Cycle (2.5 Hz at 10PP)	— 100	10 5 avg.	0.495 0.300
II. Steady State Limit Cycle (1 Hz at 40PP)	— 100	15 8 avg.	0.495 0.140 avg.
III. Steady State Limit Cycle	— 100	20 8 avg.	0.357 0.140 avg.
IV. Stall	100	6	0.495

Table 1. Elevon Dynamic Response Requirements

Motor requirements were backed out of the actuation requirements as illustrated in Table 2. Then, an analysis was made of the motor speed and torque required to meet actuator performance requirements; minimize motor weight, rotor inertia, and power semiconductor stresses; and maximize motor torque and efficiency. A computer program was then written to calculate motor performance. Input data is supplied for all the dimensions of the magnetic circuit, the B-H curves for all magnetic materials, pole enclosure, stator winding data, etc.

The computer program used was based on considerable past development work with brushless motors. The torque equation, which was derived from fundamental motor equations, had demonstrated high accuracy in many applications. Certain factors, such as stray load loss constants, were empirical, based on past brushless dc motor test data (note that these were not brushless PM motors).

The resultant program took into account the saturation of iron paths, established the equivalent air gap of the machine, and determined the operating flux level in the

motor. All mechanical data needed was computed, such as: slot area, slot fill, weights of stator laminations, stator copper, rotor core, and magnets. Dependent dimensions which were not input were also calculated; these included: magnet dimensions, stator bore, dimensions to aid the draftsman in making the stator lamination drawing, etc. All flux paths areas were determined, along with no-load flux densities, ampere-turn drops, cold and hot stator resistances, and rotor inertia.

$$T_{m(LC)} = T_{LC} (a \times \eta) + a \delta \times \omega_L^2 / n \times J_R$$

where:

$T_{m(LC)}$ = Motor torque required to drive limit cycle load

T_{LC} = Limit cycle load torque

δ_L = Peak limit cycle amplitude

ω_L = Limit cycle frequency (rad/sec)

J_R = Rotor inertia

n = Number of motors operating

a = Effective gear ratio

η = Gear train efficiency

$$T_{m(L)} = T_L (a \times \eta)$$

where:

$T_{m(L)}$ = Motor torque required to drive maximum load

T_L = Maximum load torque

$$\omega_m = a \delta_L n$$

where:

δ_L = Maximum load rate

ω_m = Motor velocity (rad/sec)

Table 2. Speed/Torque Relationships of Motor/Load

At top speed and no load, a calculation was made of the pole face loss due to stator slot flux ripple. To conserve computer time, this value was used for all torque points (note that experimentation with the computer subroutine showed no appreciable change under load). For a given speed the torque points were incremented in equal steps, starting with no load, up to whatever limit the designer chooses. For each net torque output point, calculations were then made of: developed torque, input watts, dc-amps, dc volts, motor efficiency, stator copper loss, stator iron loss, windage and friction, stray load loss, pole face loss, armature reaction, ampere-turns, specific tangential force, ampere-conductors per inch, and kW per r/min.

MOTOR CONSTRUCTION

Rotor

One of the most important requirements in the motor design was for low inertia. This means the rotor must be small in diameter and have a relatively long stack. It also means that the number of poles in the rotor will tend to be greater. A 4-pole design would tend to minimize power semiconductor switching losses, but the magnet configuration on the rotor is a compromise.

The computer program used was of particular benefit in the rotor design. The calculated dimensions of the magnets were discussed with vendors to determine the practicality of various designs. After many computer parametric studies, an 8-pole configuration was chosen. The length of the magnets in the axial direction required the makeup of a single pole assembly of several separate blocks of material. The shaft and core of the rotor (Figure 1) were made from a single piece. This configuration simplified the rotor construction and assured negligible loss in magnetic properties of that portion of the shaft used as the core flux path.

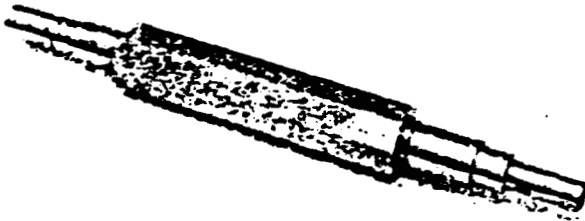


Figure 1. Motor Shaft

The magnetized blocks (Figure 2) were cemented to the motor shaft and then ground to a finished diameter by the magnet vendor. The rotor assembly (Figure 3) was completed by adding the balancing discs on each end of the rotor, banding, and pressing on ball bearings.

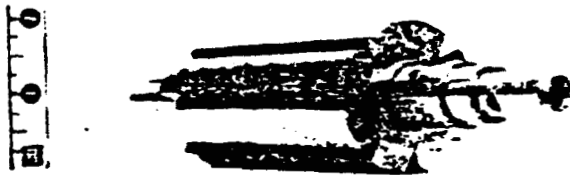


Figure 2. Magnets Attached to Shaft



Figure 3. Completed Rotor Assembly in Protective Container

The operating speed at minimum rated output was chosen to 9,000 r/min. The critical shaft speed was determined to be above 69,000 r/min. A rotor spin test at over 30,000 r/min was performed without failure.

Stator

For the stator assembly (Figure 4) laminations were punched, heat treated, and bonded into a stack. The OD of the lamination assembly was ground and then the frame was heated and shrunk in place on the OD of the laminations.



Figure 4. Stator Assembly

Since the machine was to be designed for 17 hp continuous operation, the stator conductors had to be liquid cooled. To accomplish this with a dry air gap, a nonmetallic sleeve (Figure 5) was developed to fit closely within the stator bore. Cooling fluid entered the frame on one end of the winding, was forced through the stator slots around the copper, and exited via the opposite end of the stator. This method has been successfully used on many brushless motor programs."

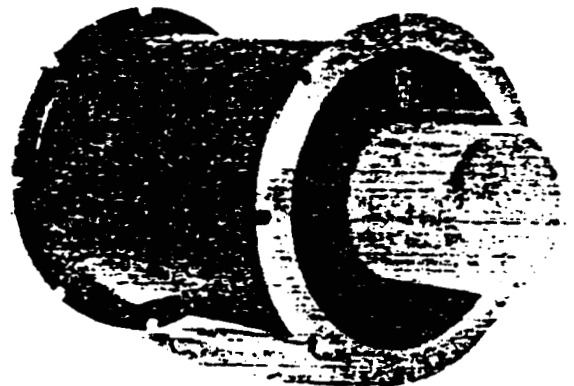


Figure 5. Nonmetallic Sleeve in Stator Bore

• Walter Slabiak and George C. Collins. Brushless Synchronous Propulsion Motor. SAE 680445 (1968).

C. W. King, George C. Collins, Walter Slabiak. Electric-Wheel Vehicle Propulsion System. SAE 690071 (1969).

Bert Sawver. Brushless Synchronous Traction Motor System Power Capability Evaluation. TACOM Technical Report No. 11265 (1971).

Before building the motor, thermal tests were run with a dummy stator segment having the same dimensions as in the motor to be constructed. The model (Figure 6) represented 2 slots (or one twelfth) of the motor stator. The copper winding used had a copper volume equal to that of the actual stator winding.



Figure 6. Simulated Pair of Stator Slots

The thermal model was insulated to prevent any cooling due to conduction, radiation, or air convection. Liquid coolant was forced to flow from one end of the model, through the slots, around the conductors in the slots, and to exit the opposite end of the simulated stator stack. The varnish build-up and the stator slot insulation were also equivalent to that in the final motor. The slot and winding were so designed that the slot fullness and the impregnation of the windings would not completely obstruct the slot space provided for the fluid to flow in a random path.

During the thermal tests various fluids were tested at a rate of fluid flow equal to 1.12 of the complete system. The power level in the copper winding was set at 68.5 watts; this was equivalent to a total loss of 822 watts in the stator assembly, as would occur at the 17 hp load point. Using FC-75 coolant (Figure 7) the winding temperature was 58°F warmer than the inlet coolant temperature at 0.041 gpm (0.492 gpm for a complete motor) and 48°F warmer at 0.13 gpm (1.96 gpm).

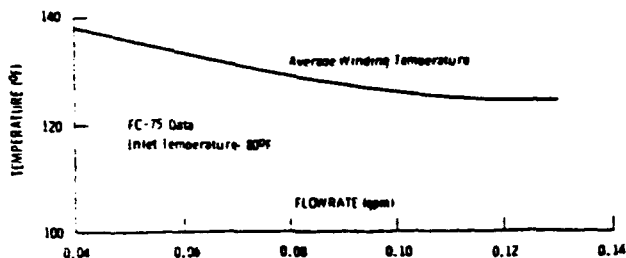


Figure 7. Stator Cooling Characteristic

PERFORMANCE

The complete motor assembly is shown in Figure 8. Overall length of the motor/brake assembly was specified to be 11.85 inches; the actual length was 11.25 inches. The motor weight goal was 17.0 pounds; the actual weight was 17.16 pounds. The calculated inertia of the rotor is 0.000363 pound feet seconds squared, or 0.000491 kilogram meters squared.

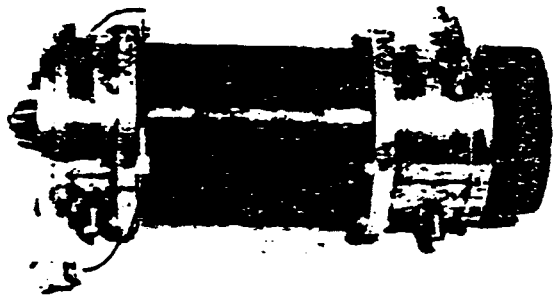


Figure 8. Complete Motor Assembly

The flux level in the final motor was higher than predicted. The calculated gap density was 35,800 lines per square inch and the measured density was 41,300 lines per square inch. This increase was primarily due to the permanent magnets having a higher energy product than the minimum value specified on the purchase order.

The estimated rotor temperature (used as input data) was too conservative (too hot) and the end turn length of the stator coils was underestimated. The motor winding was then changed to obtain the proper motor performance. As a result of being able to drop turns and increase wire size:

- The resistance obtained was equal to 77% of the original design.
- The stator inductances were approximately 53% of the original values (minimum inductance is usually desired).

The plot of motor rotational loss versus speed in Figure 9 shows the sum of watts loss due to friction, windage, iron losses, and the dynamometer coupling. Approximately 160 watts are dissipated at 9,000 r/min, which compares closely with the 177 watts calculated with the computer program. The load line of operation on the B-H curve of the magnet is 23.61. Operation at this point is highly important in minimizing the irreversible flux loss caused by elevated permanent magnet temperature.

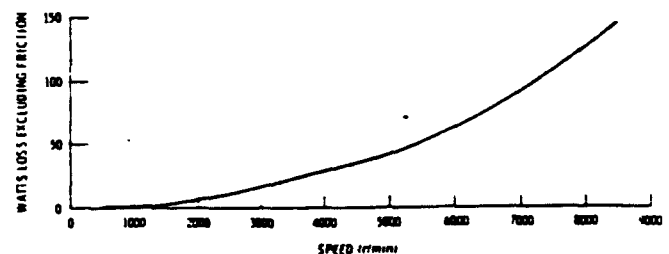


Figure 9. Rotational Losses vs. Motor Speed

The calculated motor efficiency at 120 inch-pounds torque at 9,000 r/min was 92.6% (17.136 hp). The performance measured at 120 inch-pounds and 7,923 r/min (15.086 hp) showed a total system efficiency of 89.76%. If voltage were raised to obtain 9,000 r/min, the projected system efficiency would be 90.51%. If the efficiency of the electronic control were assumed to be 95%, the motor efficiency would be 95.27%.

Figure 10 shows a plot of motor torque, battery voltage, and system efficiency versus battery current. This data was taken with a fixed commutation angle of advance of 40 electrical degrees. Since the system will actually be using 30 degrees of advance, the torque per ampere will be higher and a slightly higher efficiency will be obtained.

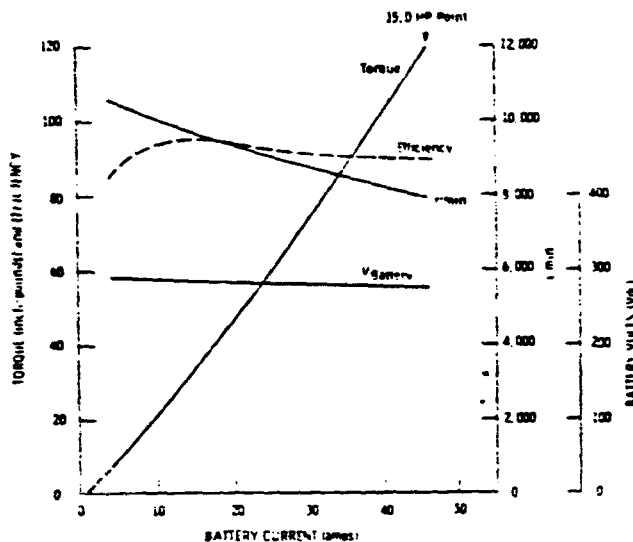


Figure 10. Motor Performance Data

More accurate efficiency numbers will be obtained when the necessary power measuring instruments are available. The separation of losses will be made by directly measuring the power input to the motor terminals.

Motor resistance at room temperature is 0.0626 ohms line to neutral. Braking torque of the machine has been evaluated, but only as a simple alternator operating into a resistive load. Braking torque of 120 inch-pounds has been achieved from 9,000 r/min down to about 450 r/min, at which point it declines linearly to zero torque at zero r/min.

ELECTRONIC CIRCUITS

In the power transistor circuit, shown in Figure 11, Q1 through Q6 perform the standard "commutator" function and Qm, L1, and Dm provide the familiar chopper circuit. Inductor L1 filters the chopper (Qm) current to the motor and uses free wheeling diode Dm to permit current flow from the stored energy in the inductor when Qm is Off.

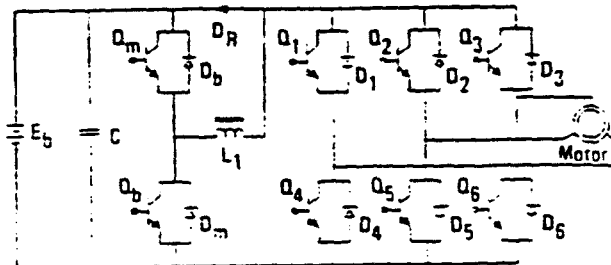


Figure 11. Power Electronics Circuits

The circuit used in braking is one that British manufacturers have used for years in battery powered trucks. In braking, Qm is Off, Qb is On, which causes current to flow through L1 in the reverse direction. When Qb is turned Off, the inductive voltage of L1 adds to the dc voltage from the motor (acting as an alternator) and exceeds the supply voltage E_b. When this occurs, current flows back into the battery via diode Dm until the battery voltage exceeds the sum of these two voltages, or the motor current level drops below the commanded level.

CONCLUSIONS

Use of rare earth in permanent magnet brushless dc motors, together with high power semiconductors, have made the electromechanical actuator a viable concept for flight control applications. Energy requirements for electromechanical actuators are proportional to load requirements, which minimizes losses.

Applications requiring high torques for long periods of time may impose a requirement for active cooling of the stator windings. However, it is possible to air or liquid-cool the stator winding and still provide a dry air gap. It may also be possible to obtain smaller stator losses by utilizing other motor configurations.

Continuing improvements in rare earth magnetic materials and the power semiconductors that control these motors should result in lower weight electromechanical actuator systems with increased performance and efficiency.